

Manufacturing Process Advancements for Flexible CIGS PV on Stainless Foil

L. J. Simpson^a, S. Wiedeman^b, J. S. Britt^b, T. L. Vincent^c, J. Hanna^c, M. J. Hilt^c, N. B. Gomez^a, J. P. Delplanque^c, M. E. Beck^b, B. S. Joshi^a, R. J. Kee^c, G. J. Kleen^a, R. B. Huntington^b, E. Sheehan^b, J. M. VanAlsburg-Westermann^b, and J. Taylor^b

^aITN Energy Systems Inc., 8130 Shaffer Parkway, Littleton, CO 80127

^bGlobal Solar Energy, Inc., 5575 S. Houghton, Tucson, AZ 85747

^cColorado School of Mines, 1600 Illinois, Engineering Department, Golden CO 80401

ABSTRACT

Substantial improvements in production cell efficiency and yield have been achieved for roll-to-roll CIGS PV on stainless foil at GSE. Large area cells (68.8 cm²) have advanced to >13% efficiency, with a maximum frequency of distribution near 11% in some production lots (Figure 1). Yield has increased from 20% to 90% (Figure 1) through process, equipment and procedural advances. These successes were partially enabled by process control and reliability improvements under activities that include ITN Energy System's subcontract with the PV Manufacturing R&D program at NREL. Improved cell integration, module construction and cell efficiency have led to modules with greater than 40 W/kg (11.1% efficiency) in fully flexible, lightweight formats. The PV Manufacturing R&D program at ITN has advanced CIGS technology through development of predictive control models, fault tolerance, in-situ sensors, and process improvements. Physics-based models for deposition processes were developed to improve process control, re-design hardware and implement fault tolerance. Process reliability and reproducibility have improved greatly by implementing fault prevention strategies, sensor/hardware failure detection, and real-time reconfiguration of systems to operate despite sensor/hardware failures.

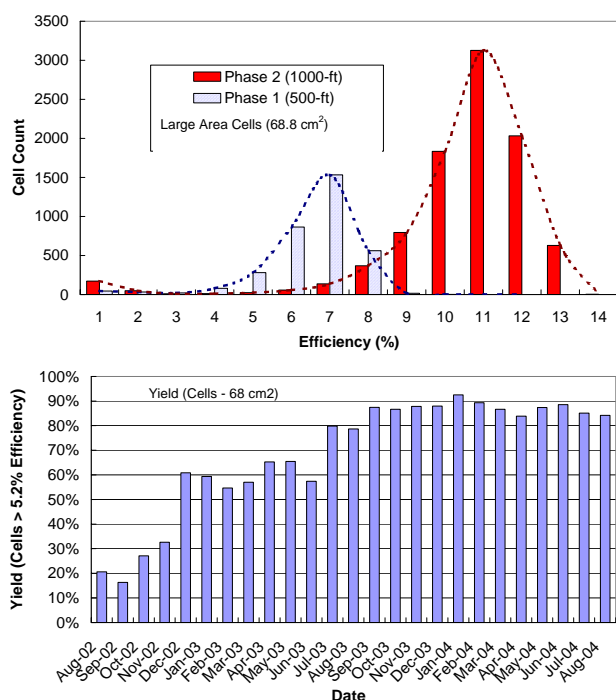


Figure 1. Efficiency and yield improvements that have occurred for roll-to-roll CIGS PV Cells produced during the PV Manufacturing R&D program.

Objective

Thin film photovoltaic (PV) technology has improved dramatically in the last few years, enabled to a large extent by substantial implementation of reliable and accurate process control. ITN Energy Systems, Inc. (ITN) and Global Solar Energy, Inc. (GSE) are following a comprehensive and systematic program to integrate intelligent process control into the manufacture of flexible, lightweight copper indium gallium diselenide (CIGS) based PV modules on the GSE production line. Process control has been a priority from the beginning of the program, enabling the development of a fully integrated CIGS module manufacturing facility in only four years and large-area cell efficiencies greater than 13%. The PV Manufacturing R&D program at GSE/ITN aims to complete a fully integrated process control development program that includes models, control platform, and diagnostic tools (sensors) for intelligent processing of PV modules, with the goal of improving CIGS module performance, process throughput, and yield. The highly successful PV Manufacturing R&D program has contributed to the manufacture of the high performance, large-area flexible PV modules.

Technical Approach

The goal of ITN's PV Manufacturing R&D effort is to develop trajectory-oriented and fault tolerant based intelligent process control using predictive physics-based process models and strategic process/film property sensors to significantly improve yield, throughput, and performance of flexible CIGS PV modules. Implementing trajectory-oriented control consists of developing mathematical relationships (models) between control variables and final product properties (system identification), reducing models into computationally efficient form(s), establishing optimum trajectories for film properties during deposition into a control platform. Process models/simulators are required for unanticipated process upsets, reactor variability/drift, and operation in unstable processing regimes where repeatability can be achieved only through dynamic feedback/feed-forward control. Fault tolerance includes detecting, locating, and isolating faults, and implementing appropriate corrective measures that prevent faults from becoming critical failures. Inadequate diagnostics and predictive models result in sub-optimal control and correspondingly higher costs through lower efficiency and yield. Sensor integration is required to provide real-time process information for quantitative assessment and control of film properties to increase reliability and maximize yield and efficiency. Finally, models and sensors must be incorporated into a robust control platform to enable autonomous and continuous manufacturing, with automatic data storage and presentation for operator monitoring.

Results and Accomplishments

GSE's manufacturing facility is fully equipped to produce 5 MW per year of flexible, lightweight CIGS PV products. Key CIGS production equipment includes: molybdenum back contact, CIGS absorber layer, cadmium sulfide, and transparent conductive oxide deposition systems; module laminators, and PV product finishing equipment. Each production deposition system is capable of processing 12-in. wide 1000-ft. long polymer or stainless steel webs in a low cost, automated continuous roll-to-roll fashion. GSE's substantial thin-film photovoltaic module process/product achievements were instrumental in receiving an R&D 100 award by R&D Magazine for being one of this year's 100 most significant technological innovations. Today, the CIGS PV modules produced at GSE are the only truly flexible PV commercially available with over 10% efficiency that can be folded/rolled for compact storage and transport and deployed extremely quickly, breakage-free. This innovative technology is being incorporated in a number of products for military and commercial applications (Figure 2).

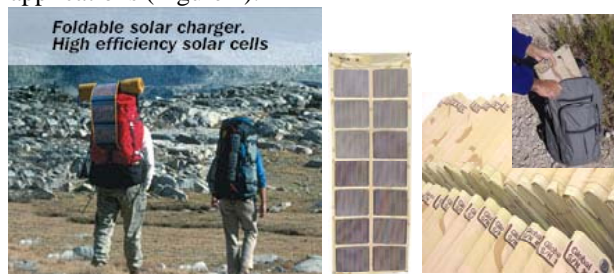


Figure 2. Representative Coleman and ICP Global Products that use GSE's CIGS PV Modules.

Outstanding improvements in CIGS cell performance have been achieved through process improvements partially enabled by advances in in-situ real-time sensing, robust process control, and high reliability operation under the PV Manufacturing R&D program. One substantial benefit from improved control/yields is accelerated evaluation through "design of experiments" to optimize process parameters for improved performance in production. Figure 1 illustrates the substantial improvements achieved during the program. In general, since the inception of ITN's PV Manufacturing R&D program, average and maximum efficiencies have increased substantially. Since this program is primarily directed at increasing average efficiency, the fact that average efficiency (normalized) has increased by more than a factor of two compared to the maximum efficiency is an indication of the benefits obtained from the PV Manufacturing R&D activities.

Continued efforts in physics based-models, fault tolerance, model-based diagnosis and decision-making algorithms have reduced fault events and improved deposition control substantially. Figure 3 illustrates the level of control attained in the CIGS deposition process, for example, during an experiment where multiple critical setpoints are changed simultaneously while still

maintaining the critical Cu/(In+Ga) ratio. Future efforts will build upon these accomplishments to complete several process control and fault tolerance tasks and implement additional process improvements.

SUMMARY/CONCLUSION

ITN and GSE, with the assistance of NREL's PV Manufacturing R&D program, are continuing to advance flexible CIGS production technology through a multidisciplinary approach focused on substantial improvements in thin-film deposition processing. Progress has been made in several areas from physics-based models to *in-situ* sensors. The design and implementation of trajectory oriented physics-based control models on production deposition systems has provided improved dynamic control, systems design, and fault tolerance. In addition, robust *in-situ* sensors have been developed and in some cases implemented to provide real-time process and product information for feedback and feed forward control. Development activities included evaporation source, flux and thin-film property sensors to provide the most relevant information for process control. These activities have resulted in outstanding improvements in CIGS cell performance (entire lots with > 10% average efficiency) and production yields of > 90%, while substantially reducing fault events due to component and system breakage. The PV Manufacturing R&D program activities have enabled rapid progress through improved process control and parameter optimization.

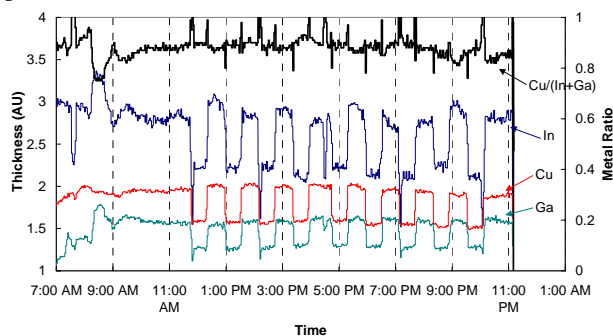


Figure 3. Demonstration of CIGS Process Control enabled by the PV Manufacturing R&D Program.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge and thank UniSource Energy Corporation and the Department of Energy's National Renewable Energy Laboratory, Photovoltaic Manufacturing R&D Program, Contract Number DE-ZDO-2-30628-07, for their support, and E. Eser, R. Birkmire, and W. Shafarman at the Institute of Energy Conversion, U. of Del., DE for their contributions.

MAJOR FY 2004 PUBLICATIONS

Hanna, Jeffrey, "Finite-Element Modeling of Thermal Behavior ...," Colorado School of Mines Thesis

Hilt, Matthew J., "Validation and Reduction of Models for High Rate Metal Vapor Effusion Sources," CSM Thesis